Regional Extreme Climate Events: Gaining understanding through Past and Present Observations and Modeling

Climate Drivers Team Final Report, FY12

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I. Purpose and Objectives

This research element supports vulnerability assessment for climate adaptation (Glick et al. 2011) by focusing on the provision of best available climate information for the region in order to inform analysis of ecosystem exposure to change. Climate in the North Central United States (NCUS) is driven by a combination that includes large-scale patterns in atmospheric circulation, the region's complex topography extending from the High Rockies to the Great Plains, and geographic variations in water and surface-energy balance. Hydroclimatic variability within the NCUS determines the sustainability of ecosystems in the region as well as the ecosystem goods and services they provide. We propose, therefore, to use a diverse set of region-specific approaches for developing a hydroclimatology that is faithful to the full range of temporal and spatial scales of climate processes in order to evaluate efficacy of climate model simulations, provide interpretation of climate change mechanisms, and advance understanding of co-variability between climate, ecosystems, and species of interest to stakeholders.

II. Organization, Approach, and Results

(1) Data-model framework

We propose a data-model framework that will integrate the paleoclimate reconstructions, recent observations, and modeling efforts for evaluation of NCUS hydrological processes from the past (late Holocene) through the future (2100 AD). Climate models are the sole tools for quantifying past and future oceanic and atmospheric circulation under different boundary conditions (e.g., in trace gases, insolation, albedo, vegetation) than those at present. Iterative comparisons of data and models provide both a better understanding of climate change and an opportunity to improve models.

<u>Research activity and focus:</u>

(a) We propose to develop a vetted database of historical and paleoenvironmental records for targeted areas in the region. The database will bring together proxy data (pollen, charcoal, macrofossil, diatoms, geochemical data, tree-ring records) and derivative products (reconstructions of snowpack, lake turnover, area burned, insect outbreaks, lake level, glacier fluctuations, stream flow, PDSI reconstructions).

(b) We propose to develop a historical daily climatology from 1950 – present that will be built with a 1-km grid increment for the NCUS. The gridded dataset will be based on the surface observation network.

(c) We propose to produce high-resolution simulations of recent climate with the Weather Research and Forecast (WRF) model driven by North American Regional Reanalysis (NARR) data. WRF simulations will have a nested domain configuration. A 12-km grid covering the continental United States will be used to simulate processes in the Great Plains. It is important that the 12 km domain extend well to the south, so as to properly capture monsoon processes and low-level moisture transport from the Gulf of Mexico within the NCUS. A nested domain with 4-km grid will be used to simulate the inter-mountain west, covering the high elevations of the Rockies. The WRF simulations will be evaluated for agreement with the gridded 1-km observations and for propagation of precipitation systems from the lee of the Rockies into the Plains, a characteristic of warm season rainfall in the Plains that is absent in global climate model simulations.

(d) We propose to produce future climate simulations by dynamically downscaling three GCM simulations (1950-2100), so as to span a range of possible future solutions, produced for the AR5. The WRF configuration when downscaling GCM data will have three domains: outer 36-km grid domain encompassing the entire CONUS and adjacent ocean regions and two interior grids corresponding to the 12-km and 4-km domains of the WRF simulations driven by NARR. Each GCM will be given observed radiative forcing for 1950-2005. The Representative Concentration Pathway 4.5 will be used for 2006-2100.

Results

(1a) Vetted database of paleoenvironmental records

The paleoclimate database consists of 1260 paleoenvironmental records, including proxies of climate (i.e., tree-rings, borehole temperatures, isotopes, diatoms, electrical conductivity, ice cores, loess accumulation), streamflow (i.e., tree rings), fauna (i.e., fossils), vegetation (i.e., pollen, plant macrofossils) and fire (i.e., tree-scars, charcoal) and is hosted at the IoE (http://www.nccscpaleoenvironmentaldatabase.com). Raw data and radiocarbon dates (when applicable) are provided in .csv format for all but tree-ring records, which are available in the NOAA database and a link is provided. Prior to incorporation into the database, data have been curated and saved in a pre-established format to allow automated meta-analyses. In addition, we have developed both radiocarbon- and calibrated age-depth models and presented them in .csv format. Fast visualization and interpretation of the data are possible by use of plots of the age-depth models and time series of the proxy data (both as a function of radiocarbon and calibrated years BP) in .pdf format. We collected metadata for all records. These metadata include site information (i.e., site name, state, coordinates, elevation and modern vegetation), data characteristics (i.e., parameters measured, resolution and span of the record), details on the chronologies associated with the records (i.e., age control, number of radiocarbon dates), authors and publications. Records, derived products and metadata are stored and backed up at the Institute on Ecosystems, MSU. (See Fig. 2 and 3 for example of site information for Blacktail Pond, northern Yellowstone.)

Although the bulk of the published data has already been collected, the incorporation of some records is contingent on the original collectors contributing them to the database. This required contacting individuals and encouraging them to contribute to the database. We worked with other database efforts (Neotoma, International Multy-proxy PaleoFire database, ITRDB Data Bank, NSIDC, NOAA) to ensure that entries were up to date. Information about the different datasets is available to support the database. Data and metadata were verified and errors corrected, and information was updated as new records have been added (Table 1).

TABLE 1: Example of metadata entries for selected sites.

State	Site	Lat.	Long.	Elevation (m)	Vegetation type	Data type	Proxy of	Parameters measured	Contact
MT	MT2-14	46.72	-112.30	1826	Grassland	Borehole temperature	Temperature	Temperature	Blackwell, D
WY	Forest Pond Lake	43.37	-109.93	2797	Forest	Charcoal	Biomass burning	Microcharcoal particles/100 pollen grains	Lynch, E.A
WY	Fremont Glacier	43.12	-109.62	4100	Tundra	Core ions	Hydrology	Ion concentration	Schuster, P
WY	Crevice Lake	45.00	-110.57	1684	Forest	Diatoms	Hydrology	Diatom percentages	Whitlock,
ND	Moon Lake	46.85	-98.15	444	Grassland	Diatoms	Salinity	Diatom percentages	Grimm, E.C
MT	Foy Lake	48.16	-114.35	1006	Forest	Diatoms, chemistry and isotopes	Hydrology	Diatom percentages	Stone, J.
CO	Archuleta Mesa	37.17	-107.27	2237	Forest	Fire scar and establishment dates	Fire events	Number of scarred trees	Brown, P.M
NE	Beaver Lake	42.45	-100.66	907	Grassland	Grain size	Eolian activity	Loess accumulation	Fritz, S. C
IA	Cold Water Cave	43.11	-91.51	370	Grassland	Optical density of luminescence	Solar luminosity	Optical density	Stoykova, D
ND	Rice Lake	48.00	-101.53	620	Grassland	Ostracode Mg/Ca	Hydrology	Mg to Ca ratio	Yu, Z.C.
CO	Bison Lake	39.45	-107.20	3255	Shrubland	Oxygen isotopes	Hydrology	O concentration	Anderson,
CO	Como Lake	37.55	-105.50	3523	Forest	Plant macrofossils	Vegetation	Plant macroffosils percentages	Shafer, D.S
MT	Forest lake	46.45	-112.16	1895	Forest	Pollen	Vegetation	Pollen percentages	Brant, L.A
IA	Cold Water Cave	43.11	-91.51	370	Grassland	Stable isotope data	Temperature	Stable isotopes concentration	Dorale, J.A
WY	Fremont Glacier	43.12	-109.62	4100	Tundra	Titium and 18O	Temperature	Stable isotopes concentration	Schuster, P
MT	Preston Park	48.72	-113.65	2150	Forest	Tree ring	Age structure	Ring width	Bekker, M.
MT	Highland Fire Outlook	45.75	-112.53	2730	Forest	Tree ring	Chronology	Earlywood/ latewood density	Briffa, K.
CO	Bennett Creek	40.67	-105.52	2301	Forest	Tree ring	Streamflow	Ring width	Woodhouse,

(1b) Historical Daily Temperature Climatology 1948 – 2012

A 30-arcsec (~800 m) resolution CONUS dataset of 1948 – 2012 daily minimum and maximum temperatures was completed. The historical climatology was developed through novel integration of weather station reports with remotely-sensed land skin temperature. Prior to data integration, thorough evaluation of station data was conducted. The quality assurance effort found that systematic temporal biases were present in station data at high elevation. A process was developed to remove these biases before data integration. With biases removed, the network's 1991-2012 minimum temperature trend was reduced from +1.16°C decade-1 to +0.106°C decade-1. This important finding suggests that higher elevation and lower elevation minimum temperature trends in the western U.S. are statistically indistinguishable, contrary to previous results. In the context of a warming climate, this artificial amplification of mountain climate trends has likely compromised our ability to accurately attribute climate change impacts across the mountainous western U.S.

The historical climatology was implemented through development of an open source statistical framework for modelling topoclimatic air temperature called TopoWx ('Topography Weather'). The objectives of the framework were to provide (1) improved temporal and spatial representations of topoclimatic air temperature; (2) grid-cell level uncertainty estimations; and (3) an impetus to increase both end-user understanding of topoclimatic dataset (TCD) limitations and end-user involvement in TCD development.

The TopoWx framework developed consisted of five components.

- First, comprehensive quality assurance procedures ensured the overall quality of the input station observation records.

- Second, homogenization procedures better ensured that artificial temperature trends from changes in station siting and instrumentation were not propagated into the historical climatology.

- Third, missing value infilling procedures produced a spatially consistent and serially complete set of input stations throughout the entire 1948–2012 time period

- Fourth, a set of several interpolation components consisted of the main spatio-temporal interpolation procedures that took the homogenized, serially complete station data as input and produced the final gridded topoclimatic temperature and uncertainty estimates. The spatio-temporal interpolation procedures included both geostatistical kriging and geographically weighted regression, and a novel application of remotely sensed land skin temperature (LST) as a spatial predictor of topoclimatic air temperature. For observations of LST, the Moderate Reso- lution Imaging Spectroradiometer (MODIS), 8-day, 1-km LST product was used. MYD11A2 from the Aqua satellite was used since its day and night overpass times more closely correspond to the diurnal timing of maximum and minimum temperature in the CONUS.

- Fifth, uncertainty was assessed by means of moving window regression kriging prediction standard error to account for local variability (non-linearity) in station monthly normals through deterministic variability (spatial trend) and autocorrelated stochastic variability. The uncertainty was expressed in terms of prediction confidence intervals.

The historical gridded analysis includes daily maximum and minimum temperature on an 800 m grid for the conterminous United States. The data are hosted by the NC CSC and currently updated on an annual basis.

(1c) High resolution Weather Research and Forecast (WRF) model simulation 1980 – 2010

A 4-km dynamical downscale dataset was generated with the WRF model in order to capture detailed orographic precipitation and explicit representation of convective precipitation. The WRF simulations were driven by Climate Forecast System Reanalysis, meaning the WRF data provide an historical simulation that can be compared to observations. The simulation domain stretches from Idaho to eastern Nebraska and Montana to the Texas panhandle.

Hourly surface variables from the 30-yr historical simulation are hosted by the NC CSC.

(1d) WRF dynamical downscaling of three GCM simulations (1950-2100) for the AR5

This work was not funded through the NC CSC RFP process following FY2012.

(2) Water balance change

(a) We propose to apply the one-dimensional water balance model to the 1-km gridded observations. From the water balance, we will simulate MODIS landcover and LAI to evaluate response of vegetation to hydrological changes.

(b) We propose to apply the one-dimensional water balance model to WRF output to evaluate its capability for simulating recent change (using simulations driven by NARR) and to produce an ecosystem-relevant projection of future changes.

(c) We propose to apply the one-dimensional water balance model to existing downscaled data sets that provide sufficient data to do so. This may be interpreted as a screening process that addresses one necessary component that climate model simulations (downscaled or not) must simulate well in order to be appropriate for use in ecosystem vulnerability analysis.

(d) We propose to develop from paleo reconstructions of the late Holocene a synoptic climatology of extreme events (drought, severe winters, floods) to describe their regional distribution in the current neoglacial period that will provide context for recent change.

(e) We propose to identify conditions associated with extreme climate events in downscaled simulations of late Holocene and projected future climate to identify whether future extremes might result from emergent climate mechanisms. Similarly, we will work with ecosystem scientists to identify extreme ecological events (that may or may not be extreme climate events) and determine climate conditions associated with them in both observations and historical climate simulations.

Results

(2b), (2c), (2d), (2e)

These activities were not funded through the NC CSC RFP process following FY2012.

(2a) One-dimensional water balance model applied to 1-km gridded observations

Work has continued on developing inputs needed for one-dimensional water balance model. A regional version of the MOD16 evapotranspiration algorithm has been developed. In order to be applied, the algorithm will require additional weather input information. Next steps in gridded data development will proceed as follows: humidity, solar radiation, and precipitation.

(3) Linkages between Climate and Ecosystem Scientists in the University Consortia

The following research and activities will foster close collaboration between climate and ecosystem system scientists.

Research activity and focus:

(a) We will remain in close dialogue with ecosystem scientists as they define candidate Ecological System Types for analysis and as the modeling approaches used to simulate them are determined. In the first year, the dialogue will be maintained by quarterly teleconferences, additional project-specific teleconferences as needed, and at least one jointly held workshop.

(b) We will provide expert information on climate change in support of the delivery of observational and model data for use in identifying co-variability between climate and ESTs. This will entail much more than passing along data. Our dialogue will produce guidance on temporal and spatial scales that are appropriate for the use of climate data, and this initial collaboration will begin the first steps in building region-wide recommended uses of climate data.

(c) We propose to build a proof-of-concept ecosystem model within one of the selected ESTs. We will use the RHESSyS model, a watershed model that will be placed in a targeted watershed, and provide validation from the past hydrologic/ecosystem.

Outcomes

(3a) Ecological System Type: Whitebark Pine

FY2013 CSC Project: Information implementation of the Greater Yellowstone Coordination Committee's Whitebark Pine Strategy based on climate sciences, ecological forecasting, and valuation of WBP-related ecosystems services

The paleoclimate database contains pollen and plant macrofossil records from lake sediments from ten sites in the GYA. These records provide information on whitebark pine (WPB) presence/abundance at a watershed scale and multi-decadal to centennial time resolution over the past 15,000 years (Fig. 4). Paleoclimate reconstructions have been independently derived from stable isotopic, diatom, and geochemistry data and from paleoclimate model simulations. Iglesias et al. (2015) used records in the database to understand the regional trend in WPB presence/absence/abundance during the postglacial period. Through the use of Generalized Additive Models (GAMS), we visually compared GAMS results to the paleoclimate data and identified qualitative relationships between climate and WBP (e.g., cold/abundant WBP; warm/less abundant WBP) (Fig. 5). We also explored the role of fire in explaining how and why each site deviated from the regional trend by comparing the residuals from each time series to charcoal (i.e., fire history) data, which are available for some sites. WBP growth rates over the past 800 years in GYA have been derived from tree-ring data. We compared trends in WBP growth rates with independent climate data for this period to determine the response of WBP growth to extreme climate fluctuations, specifically megadroughts during the Medieval Climate Anomaly (~800-1200 years ago) and the cooler conditions in the Little Ice Age (~100-500 years ago). The results of these analyses allowed us to draw inference about the sensitivity of WBP to a range of climatic and biotic conditions.

(3a) and (3b) Ecological System Type: Grassland in Midwest tallgrass prairies and Greater Yellowstone montane meadows

FY2012 NC CSC Directed Funding for Ecological Impacts foundational science area.

Tallgrass Prairie System – Kristin Kane and Diane Debinski

Global climate change models predict that future climate trends in Iowa are expected to be highly variable, with increased temperatures and more variable rain events, leading to an increased probability of drought. Biodiversity threats to grasslands include habitat fragmentation and loss, the decoupling of disturbances such as grazing and fire, and invasive plant species such as tall fescue. Climate change is expected to add to these existing stressors and further threaten these ecosystems. Our project goals were to develop models for key grassland plant species as a basis for forecasting responses to climate change and model the responses of these species to climate change.

Plant species occurrence records were obtained from field based data collected in 12 study sites in the Grand River Grasslands of Iowa and Missouri. Current (1950-2000) and future (2040's) climate variables were derived at 30 arc seconds (~1km) resolution from the Worldclim dataset (www.worldclim.org). We modeled current and future distributions of 31 grassland plant species using the species distribution modeling software Maxent version 3.3.k.

Our results showed that Twenty-eight plant species are predicted to experience reductions in their habitat suitability by 2040. For example, very few areas of suitable habitat (Green areas) are predicted to exist for tall fescue (Festuca arundinacea) by 2040 (Fig. 1). Suitability becomes more homogenous for 3 plant species (Fig. 2). The climate variables that have the most influence on our predictions are annual precipitation and precipitation in the driest quarter of the year.

Greater Yellowstone Ecosystem – Nathan Piekielek and Diane Debinski

Regional models of global climate change for the northern Rocky Mountains predict warmer temperatures, diminished amounts of precipitation, and decreased snowpack, which could have significant impacts on the plant community of the region. Changes in the plant community composition could have repercussions across the system. Biotic changes could include modification of the distribution and abundance of insect pollinators or mammalian herbivores; abiotic changes could include modification in fire regimes. Our project goals were to assess changes in vegetation condition and measure woody encroachment in montane meadows of the Greater Yellowstone Ecosystem over the past 15 years, which included several years of mild to extreme drought conditions.

In our analysis we quantified: 1) variation in annual productivity from 2000 to 2012 using MODIS normalized difference vegetation index (NDVI) and 2) the rate and extent of woody encroachment change from 1994 -2011using 15 yrs of National Aerial Photography Program (NAPP) digital orthophotos (DOQs). While we expected that we might see evidence of a long-term drought, the strongest signal that we observed was recovery from a roughly 10-year drought that lasted from the late 1990s through 2006, with re-entry into drought conditions in 2012 (Fig. 3). However, interannual variability was much stronger than any longer-term trend in this time-series. With respect to woody encroachment, the primary change that was observed was seedlings that were too small to be detected at a 1-meter resolution in the earlier time-period became observable after ~15yrs of growth. In a small proportion of the meadows, we observed more dramatic conifer seedling encroachment or conifer loss.

(3c)

This work was not funded through the NC CSC RFP process following FY2012.

(4) Stakeholder Engagement

The climate drivers team will engage stakeholders via partnerships with USGS science centers, informal communication with LCC, and individual projects. For instance, discussion with the Plains and Prairie Potholes LCC director already indicates the peer-reviewed report on existing projections will be highly useful when engaging their stakeholders.

Outcomes

The climate drivers team is grateful the NC CSC moved forward with a peer-reviewed report on CMIP5 projections for the LCC.

(5) Publications

Behnke, R.J., S. Vavrus, A. Allstadt, T. Albright, W.E. Thogmartin, and V.C. Radeloff. Evaluation of downscaled, gridded climate data for the coterminous United States. Submitted to Ecological Applications.

Behnke, R.J., A. Ballantyne, S. Dobrowski, J.M. Graham, Z. Holden, and S. Running. A recent geographic, seasonal, and diurnal climatology of humidity in the United States using national, regional, and local station networks. In preparation for Journal of Hydrometeorology.

Behnke, R.J., A. Ballantyne, S. Dobrowski, J.M. Graham, Z. Holden, and S. Running. An evaluation of gridded humidity data sets for the United States: Do we still need to estimate humidity? In preparation for Journal of Hydrometeorology.

Iglesias, V., Krause, T.R., Whitlock, C. 2015. Complex response of white pines to past environmental variability increases understanding future vulnerability. PLOS ONE. DOI: 10.1371/journal.pone.0124439, April 17, 2015.

Kane, K., D. M. Debinski, C. J. Anderson, J. D. Scasta, D. M. Engle, and J. R. Miller, 2016: Grassland Community Restoration in the Face of Climate Change. Submitted to Restoration Ecology.

Oyler, J.W., S.Z. Dobrowski, Z.A. Holden, and S.W. Running, 2016. Remotely sensed land skin temperature as a spatial predictor of air temperature across the conterminous United States. Submitted to J. Applied Meteorology and Climatology

Oyler, J. W., S. Z. Dobrowski, A. P. Ballantyne, A. E. Klene, and S. W. Running, 2015: Artificial amplification of warming trends across the mountains of the western United States. Geophys. Res. Lett., 42, 153–161, doi:10.1002/2014GL062803.

Oyler, J. W., A. Ballantyne, K. Jencso, M. Sweet, and S. W. Running, 2015: Creating a topoclimatic daily air temperature dataset for the conterminous United States using homogenized station data and remotely sensed land skin temperature. Int. J. Climatol., 35, 2258–2279, doi:10.1002/joc.4127.

(5) Presentations

Behnke, R.J. Development of high resolution gridded dew point data from regional networks. North Central Climate Science Center Open Science Conference, Fort Collins CO, May 2015.

Behnke, R.J., A. Ballantyne, S. Dobrowski, J.M. Graham, Z. Holden, and S. Running. Assessment and improvement of high resolution daily dew point estimation. Annual Meeting of the American Association of State Climatologists, Stevenson WA, July 2014.

Behnke, R.J., A. Allstadt, J. Oyler, and S.J. Vavrus. An evaluation of observationally based, high resolution gridded data sets over the continental United States. National Climate Predictions and Projections Quantitative Evaluation of Downscaling Workshop, Boulder CO, August 2013.

Debinski., D. M. Linking Field Research with Spectral Data to Quantify Interannual Variation in Productivity and Phenology in Grassland Communities. NASA Goddard Space Flight Center, Biospheric Sciences Seminar, Greenbelt, MD, June 1, 2012.

Debinski. D. M. Working with landowners to manage and conserve tallgrass prairie biodiversity: Ecological and sociological challenges and successes. University of Colorado, Boulder, August 30, 2013.

Kane K., D.M. Debinski, C. Anderson, J.D. Scasta, D.M. Engle, and J.R. Miller. 2013. The projected effects of climate change on plant species distributions in grasslands of Iowa. 98th Annual Meeting of the Ecological Society of America, Minneapolis, Minnesota, August 2013.

Oyler, J.W., S. Dobrowski, A. Ballantyne, A. Klene, and S.W. Running (2014), Artificial amplification of elevation-dependent warming in the western U.S. MTNCLIM 2014 Mountain Climate Research Conference, Midway UT, September 2014.

Oyler, J.W., A. Ballantyne, K. Jencso, M. Sweet, S.W. Running, and R. Behnke (2014), A topoclimatic air temperature dataset for the conterminous U.S. Annual Meeting of the American Association of State Climatologists, Stevenson WA, July 2014.

Oyler, J.W., A. Ballantyne, K. Jencso, S.W. Running, M. Sweet, and R. Behnke (2013), A landscape-scale 1948-2012 daily spatial temperature dataset for the conterminous United States. National Center for Atmospheric Research Next Generation Climate Data Products Workshop, Boulder CO, July 2013.

Wang, Y., B. Geerts, C. Liu, 2015: Regional climate simulations of cold-season precipitation and snowpack over the US northern Rockies: validation and examination of factors controlling the precipitation distribution, 27th Conference on Climate Variability and Change, 95th AMS Annual Meeting, Phoenix, AZ, 4-8 January, poster.

III. Next Steps

This report concludes the coordinated activity of this climate drivers team. Each team member may continue to work under separately funded projects through the North Central Climate Science Center.